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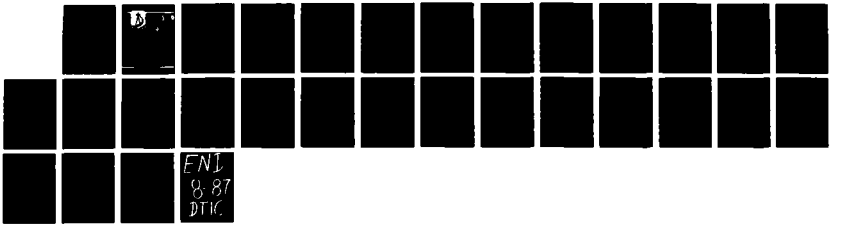

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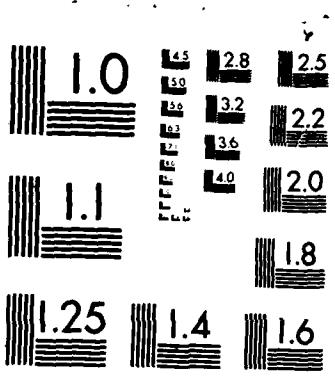

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CALIBRATION AND VALIDATION OF A SOLID-STATE ANOMALOSCOPE

George A. Geri
University of Dayton
Research Institute
300 College Park
Dayton, OH 45469

Lt David F. Neri, MSC, USNR
Naval Submarine Medical
Research Laboratory
Naval Submarine Base
Groton, CT 06349-5900

AIR FORCE HUMAN RESOURCES LABORATORY
BROOKS AIR FORCE BASE, TEXAS 78235

NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY
GROTON, CONNECTICUT 06349-5900

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Solid-state anomaloscopes whose stimuli are derived from light-emitting diodes are less expensive and simpler than conventional anomaloscopes. This effort assessed the test-retest reliability and the validity of one solid-state anomaloscope, and obtained normative data. Reliability and validity were assessed through the classification of 36 color-defective subjects into one of five categories defined by degree of defect. When all color defectives were considered, both the validity and reliability of the solid-state anomaloscope were found to be high. The primary stimuli of the solid-state anomaloscope were less well separated in chromaticity space, although there was no evidence that this limitation resulted in the incorrect classification of anomalous trichromats as dichromats. The solid-state anomaloscope appears to be an acceptable alternative to standard anomaloscopes for both research and clinical applications.

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SUMMARY

An anomaloscope is an instrument used to identify and classify certain types of colorblindness. Most standard anomaloscopes are expensive, optically complex, and difficult to calibrate. A recently designed solid-state anomaloscope, which uses light-emitting diodes, is inexpensive, portable, and more easily maintained than conventional anomaloscopes. Before a new anomaloscope can be accepted, however, it must be established that it can classify various types of colorblindness reliably and in a manner consistent with the instruments which have been used for this purpose for over 100 years. To determine whether this is the case, 36 colorblind individuals were classified on the solid-state anomaloscope, on a standard anomaloscope, and then again on the solid-state anomaloscope. Of the 36 individuals tested on both anomaloscopes, 31 (or 86%) were classified identically. Of the 34 individuals tested twice on the solid-state anomaloscope, 32 (or 94%) were classified identically. The authors conclude that the solid-state anomaloscope is an acceptable alternative to more conventional anomaloscopes for use in the testing of large numbers of individuals for colorblindness by organizations such as the armed forces. It could be used in place of conventional anomaloscopes, which are often unavailable due to their high cost and mechanical complexity. The solid-state anomaloscope could be used to more accurately establish the type and degree of colorblindness of individuals who give ambiguous results on the other, less complete, color vision tests currently in use.

PREFACE

The research reported here was performed in support of Aircrew Flying Training Research and Development at the Operations Training Division of the Air Force Human Resources Laboratory, Williams Air Force Base, Arizona. The authors thank P. Wetzel for his help in evaluating the anomaloscope timer circuitry, Dr. S. Luria for his critical reading of the manuscript, Dr. R. Kintz for the loan of his anomaloscope, and Dr. Elizabeth Martin for her assistance in all aspects of this research.

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I. INTRODUCTION

The major objective of the present effort was to compare the color-defective classifications obtained using the Kintz solid-state anomaloscope to those obtained using a standard Nagel anomaloscope. In the remainder of this section, we will give a brief exposition of color vision, color vision defects, and anomaloscopes.

Human color vision is a complex process, and many of its manifestations are still not well understood. Therefore, virtually any description of color defects will be contested by someone. Our purpose here is to cursorily acquaint the reader with the various terms that will be used throughout this report. Other more complete sources (Hurvich, 1972) should be consulted for descriptions of the experimental results on which current theories of color-defective vision are based. Similarly, Willis and Farnsworth (1952) may be consulted for a more detailed description of conventional anomaloscopes and an historical perspective on their use.

Definition of Trichromacy

Sir Isaac Newton (1704) first noted that two spectrally distinct lights (e.g., red and green) could be added together to produce a third light (in this case, yellow) which appeared to the human eye to contain neither of its constituents. Later research (begun by Maxwell, 1855) demonstrated that any light could be visually matched by combining, at most, three appropriately chosen lights, known as primaries. This experimental finding was recognized as consistent with a theory proposed by Thomas Young (1802) that the retina contains three "particles" sensitive to the three principal colors. Young's three particles are now identified with the three cones of the retina, whose photopigments absorb maximally at about 565, 535, and 420 nanometers (nm) (Bowmaker & Dartnall, 1980), and which will be referred to in this report as the red, green, and blue cones, respectively. Although the human eye can distinguish thousands of colors, this small number (three) of spectrally discrete receptors necessarily limits the number of color perceptions relative to the virtually infinite number of realizable physical stimuli. This limitation is referred to as trichromacy, and color systems manifesting it are termed trichromatic.

Normal and Defective Color Vision

It was recognized as early as 1905 by Ewald Hering (see Hurvich & Jameson, 1957) that a simple three-component theory of color vision was not adequate to explain some very fundamental visual phenomena. It was known, for instance, that certain colors--namely blue (470 nm), green (500 nm), yellow (585 nm), and red (670 nm)--were unique in that their hue does not change when their luminance changes, and in that they form pairs which cannot coexist (i.e., when mixed, produce a color that contains neither of the original colors). These unique colors are the psychological primaries and are notable in that there are four, in contrast to the three presumed primaries of the trichromatic scheme. These observations and others led Hering to postulate a so-called opponent-process organization in which a single visual "receptor" would show one response when stimulated by red light and another when

stimulated by green light. Other "receptors" would similarly code blue and yellow. There is no inherent contradiction between the trichromatic and opponent-process theories. Current color vision theory recognizes that trichromacy obtains at the photoreceptor level, and that subsequent neural mechanisms combine the trichromatic signals into opponent processes. It is in the context of these higher-order opponent processes that human color vision defects can best be understood.

As concerns their color vision, most people (90% to 92%) are classified as normal trichromats. Trichromats are so defined because they require exactly three independent primaries to match a light of arbitrary color. Normal trichromats in particular are characterized by their use of proportions of the three primaries within a specified range. The least severe form of color defect is known as anomalous trichromacy. Anomalous trichromats also require three primaries to make their color matches, but the proportions of the three primaries they use are different from those of normal trichromats. Two types of anomalous trichromacy can be identified, depending on whether the defect is in the red-green or blue-yellow systems. Blue-yellow defects are very rare, and so only the red-green defects will be discussed here. If the red component of the red-green system is affected, the resulting condition is known as protanomalous trichromacy. Observers with this condition are less sensitive to red light and hence require more red in a red-green mixture to match yellow.[1] Protanomalous trichromats comprise 1% to 2% of the male population.[2] If the defect is in the green component of the red-green system, the resulting condition is known as deuteranomalous trichromacy. Deuteranomalous trichromats require more green in a red-green mixture to match yellow and comprise 4% to 5% of the male population.

The next most severe form of color defect is known as dichromacy, which is so named because individuals with this condition need only two primaries to match an arbitrary light. Again, we will consider only defects in the red-green system; and further, although it is somewhat of an oversimplification, dichromats will here be considered to have lost either the red or green cone photopigment. If the green photopigment is absent, the resulting condition is called deuteranopia; and if the red photopigment is absent, the resulting condition is called protanopia. Both deuteranopes and protanopes are able to match any proportion of the red and green primaries to a yellow comparison light if they are permitted to adjust the intensity of the yellow light. Deuteranopes and protanopes can be most easily distinguished by the fact that the latter group is very much less sensitive to longer-wavelength (red) light and hence matches those lights with a yellow light of correspondingly reduced intensity. Deuteranopes and protanopes each comprise 1% to 2% of the male population.

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[1] The addition of red and green light to match a given yellow is known as a Rayleigh match and will be discussed in detail later.

[2] There are approximately one-twentieth as many female as male color defectives in all categories described here.

Anomaloscopes for Color Vision Testing

An anomaloscope is a device with which an observer makes a visual match to a given test light by adjusting the proportion of two appropriately chosen primary lights which are mixed together. In most anomaloscopes, the primary lights are red and green, and the test light is yellow. This choice was influenced by the observation of Lord Rayleigh (1881) that the proportion of red to green required to match a given yellow can vary substantially from person to person and may be taken as an indication of differences in color vision. The anomaloscope is an important tool for distinguishing the various forms of color-defective vision. However, since other color vision testing devices are easier to obtain and to use, they are often substituted for anomaloscope testing. The most common of these devices use plates or caps whose colors are chosen to confuse persons with known color vision defects. Although these devices are generally useful, they can distinguish only relatively broad classes of color defects, and too much reliance is placed on them by practitioners with little interest in or knowledge of color vision defects. The result often is an incomplete, hence inaccurate, diagnosis.

Despite their unique value, anomaloscopes are not widely used because they are expensive and hence, not readily available. Their high cost is due in part to the mechanical and optical complexity required to produce bright narrow-bandwidth lights and present them in a controlled manner. This complexity itself discourages use of the anomaloscope, in that it makes maintenance and calibration of the instrument difficult. Recently, Kintz (1983) described a solid-state anomaloscope which uses light-emitting diodes (LEDs) as stimuli, thereby reducing the expense and complexity of light source regulation and wavelength control (Piantanida, 1976; White, Wolbarsht, & Tieger, 1975). Further, the LEDs are in the form of bicolor light bars, which avoids the optical alignment problems of other solid-state anomaloscopes (Dain, Strange, & Boyd, 1980). In short, the Kintz anomaloscope is a compact, portable, and inexpensive instrument that can be used for classification of red-green color defectives in both clinical and research settings. However, before such an instrument can be adopted for general use, it must be established that classifications obtained using it are comparable to those obtained with more conventional instruments.

We report here an evaluation of the reliability and validity of the Kintz anomaloscope. As suggested by the National Research Council (NRC) Committee on Vision (1981), reliability was judged by test-retest data, and validity by comparison with a standard Nagel anomaloscope. Protan and deutan[3] observers were tested on both anomaloscopes, and normative data for the Kintz anomaloscope were obtained from a group of normal trichromats in order to establish the distribution of matching midpoints (MMPs) and matching ranges (MRs) needed for classifying color-defective observers. In addition, we compared the method of limits and the method of adjustment for obtaining Rayleigh color matches.

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[3] The term "protan" includes protanopia as well as all degrees of protanomaly, and the term "deutan" includes deuteranopia and all degrees of deuteranomaly.

II. METHOD

Subjects

All data were obtained from 20 deutans, 16 protans, and 43 normal trichromats. Most of the color-defective subjects were recruited from the Hartford, Connecticut, area through newspaper advertisements and were paid $7.00 per hour. Six color defectives and all of the normal trichromats were recruited from among the military and civilian personnel at either the Naval Submarine Base (Connecticut) or Williams Air Force Base (Arizona) and were not paid for their participation.

The subjects were first screened using either the AO-HRR or the AO color-test pseudoisochromatic plates. The protan and deutan observers were then given the Farnsworth-Munsell 100-Hue Test and were tested once on the Nagel anomaloscope and twice on the Kintz anomaloscope. The normal trichromats were tested on the Kintz anomaloscope only. Shown in Table 1 are the protan/deutan classifications of the 36 color defectives who participated in the present investigation. The classifications were made on the basis of the pseudoisochromatic plate test. Also shown is the age of each subject and each subject's error score on the 100-Hue Test.

Apparatus

The solid-state anomaloscope, which is the object of this investigation, was described by Kintz (1983). The anomaloscope comparison and primary lights were derived from LED bicolor light bars: the yellow comparison light from one half of an HP-2950, and the primaries from an HP-2965. The relative outputs, as a function of wavelength, of the three LEDs comprising the HP-2950 and HP-2965 bicolor light bars used in the solid-state anomaloscope are shown in Figure 1. The peak wavelength of the yellow component of the HP-2950 is 583 nm, and its half-amplitude bandwidth is about 37 nm. The peak wavelength of the green component of the HP-2965 is 565 nm, and its bandwidth is about 28 nm. The peak wavelength of the red component of the HP-2965 is 635 nm, and its bandwidth is about 41 nm. A Nagel Model I anomaloscope was used as the comparison standard. The circular bipartite field for both anomaloscopes was about 1.75 degrees in diameter.

Procedure

All color-defective subjects (except KL, #15) were pretested using the pseudoisochromatic plates and the Farnsworth-Munsell 100-Hue Test. Both tests were administered under CIE Illuminant C, which also illuminated the white surface to which the subjects adapted during anomaloscope testing. The AO-HRR test is designed to assess protan, deutan, and tritan defects. Following standard testing procedures, the subjects were first shown four demonstration plates, three of which had symbols (cross, circle, or triangle) and one of which was blank. The subjects were then asked to identify which symbols were present on the test plates and in what quadrant of the plate they were located. The FM 100-Hue Test consists of 85 colored papers mounted on small plastic caps. The 85 paper samples represent a series of perceptually

Table 1. Screening Data for the Deutan (D) and Protan (P) Subjects

Subject	Age	FM-100 Error Score	AO-HRR Classification
1. MA	44	56	Mild P/D
2. AA	32	168	Strong-D
3. JL	37	100	Medium-P
4. KT	22	116	Medium-P
5. RF	52	156	Strong-P
6. FR	20	136	Medium-P
7. JD	39	210	Strong-D
8. GA	37	146	Medium-D
9. PN	30	66	Medium-D
10. EO	33	118	Medium-P
11. LD	--	192	Medium-D
12. SS	33	208	Medium-P
13. BH	51	80	Strong-P
14. MT	31	208	Strong-D
15. KL	21	--	--
16. MS	28	132	Medium-P
17. LM	22	182	Medium-P
18. PB	28	104	Mild-P
19. HA	70	480	Strong-D
20. RP	--	292	Medium-D
21. JH	32	136	Medium-P
22. AH	36	230	Medium-D
23. GO	24	170	Medium-D
24. RC	39	64	Medium-P
25. GD	42	120	Medium-P
26. DS	22	158	Medium-D
27. GH	26	120	Strong-D
28. DW	48	152	Medium-P
29. DP	29	232	Medium-D
30. SL	56	162	Strong-D
31. DN	30	100	Medium-D
32. WD	41	44	Mild-D
33. JR	31	50	Mild-D
34. AM	42	84	Mild-D
35. HF	39	122	Medium-P
36. PS	55	172	Strong-D

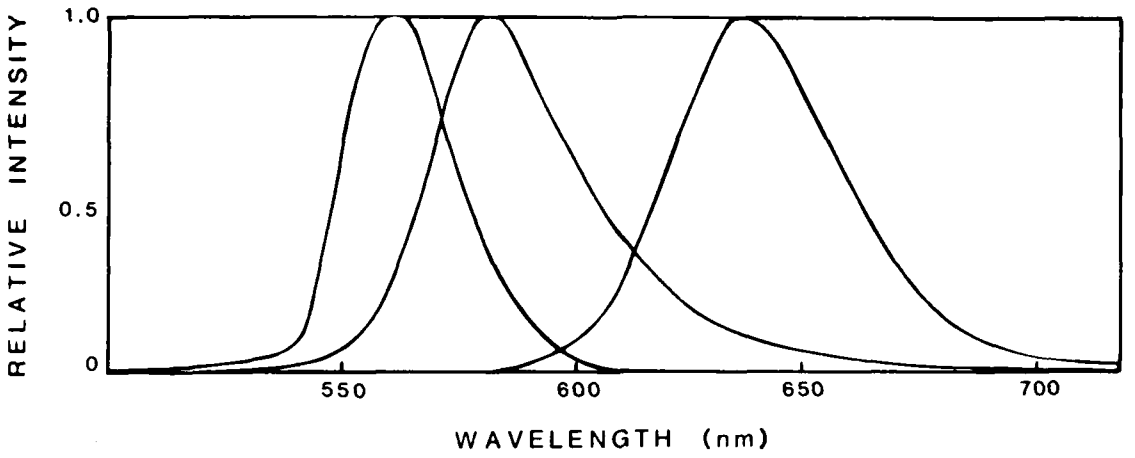

Figure 1. Relative Outputs as a Function of Wavelength of the Three Light Emitting Diodes Used in the Kintz Solid-State Anomaloscope.

equally spaced hues, and they are divided into four series of 21 to 22 samples each. Each of the four series includes two fixed color endpoints. The subjects were asked to arrange the randomized samples such that they formed a continuous series from one of the fixed endpoints to the other. The subjects were allowed 2 minutes for each of the four series. The FM 100-Hue Test gives some indication of the color confusions of color-defective observers, and the total error score was found by Lakowski (1971) to correlate with both anomaloscope matching range and wavelength discrimination.

The subjects were next tested on the two anomaloscopes. The bipartite field of the Kintz anomaloscope was viewed at a distance of about 25 centimeters under ambient illumination of 0.05 foot-Lambert provided by Illuminant C. For testing on both anomaloscopes, subjects were shown either the green or red primary field and were allowed to adjust the intensity of the yellow comparison field to obtain a complete color match or, failing that, a brightness match. Various red-green ratios were then presented by alternating between the red and green extremes thus bracketing the matching range. For each red-green ratio, the subjects were asked to fixate alternately the center of the bipartite field and an adapting surface also illuminated by Illuminant C and located about 1 meter from the subject. The subjects were instructed to determine, within 2 seconds after they had been fixated, whether the two fields matched exactly.

Approximately half of the subjects were tested first on each instrument. A retest was then performed on the Kintz anomaloscope, in most cases on the next day but always within 2 days of the original session. All testing was done monocularly, with the subject using his preferred eye. Provided their glasses or contact lenses were not tinted or otherwise colored, subjects were allowed to use them during testing.

Normal Observers

All observers whose data were used to establish norms for the Kintz anomaloscope were first tested on one of the two AO pseudoisochromatic plate tests. Of the 46 subjects so tested, 43 were classified as normal. For these 43 subjects, MMPs and MRs were obtained on the Kintz anomaloscope using a method of limits procedure. The subjects were presented with successive red-green primary settings and were asked to obtain a match by adjusting the luminance of the yellow comparison stimulus. The observers were instructed to alternate their gaze between the anomaloscope fields and a 0.08 fL white surface with a color temperature approximating that of CIE Illuminant C. They were further instructed to declare a match only when the anomaloscope fields appeared identical in color, within 2 seconds of fixating their center. MMPs were also obtained using a method of adjustment for all 43 subjects classified as normal on the pseudoisochromatic plates. The subjects were presented with non-matching anomaloscope fields and were asked to obtain a match by adjusting both the red-green ratio and the test field luminance. The viewing procedures and color-match criteria were the same as in the method of limits procedure described above.

Anomaloscope Calibration

As presently designed, the solid-state anomaloscope makes no provision for presenting either the red or green primary alone. We, therefore, used an indirect method to determine the intensity of the red and green LEDs as a function of the anomaloscope scale setting. The method involved blocking the green primary using a suitable cut-off filter, measuring the luminance of the red primary, correcting that luminance for the transmission of the blocking filter, and using the corrected intensity of the red primary and the measured total luminance to obtain the intensity of the green primary.

To block the output of the green LED, we used a Corning CS 2-61, red, cut-off filter. The transmittance of this filter is 50% at 615 nm and 1% at 600 nm (for a complete transmission curve, see Wyszecki and Stiles, 1967, p. 77). The luminance of the remaining red primary light was then measured and corrected for the amount of red LED light absorbed by the blocking filter. This correction was made by multiplying, at 2.5 nm intervals, the transmission of the blocking filter by the relative output of the red LED. The area under the resulting curve was then compared to that under the original red LED output curve. The ratio of the two areas was 0.74, and this was taken as the factor by which the original red LED output had been reduced by the filter used to block the green LED output. Finally, the intensity of the green primary was determined by subtracting the estimated red primary intensity from the total intensity of the primary field. It should be noted that although all measurements were made in luminance units, the outputs of the red and green LEDs are not specified in those units. This is because the spectral output of the red primary was not corrected by the photopic luminosity function before the subsequent corrections were made for the transmittance of the blocking filter. Therefore, although reference is made throughout this report to the luminances of the red and green primaries (designated R and G, respectively), this term has a different meaning for the primaries of the two anomaloscopes. Consequently, the R and G values given for the two anomaloscopes cannot be directly compared. This does not, however, affect the comparison of classifications obtained on the two anomaloscopes.

Shown in Figure 2 is the logarithm of the ratio of the green and red primaries (log G/R) as a function of the scale readings on the Kintz and Nagel anomaloscopes. The proportion of the red primary (R/(R+G)) as a function of scale reading for each instrument is shown in Figure 3. These data indicate that the test stimuli and primaries of the Nagel and Kintz anomaloscopes are not spectrally identical. For this reason, it would be inappropriate to directly compare the MMPs and MRs for the two instruments. Such a comparison would be possible, however, if the various stimuli were transformed to a common color system, and if then, the midpoint and range data were given in terms of equally perceptible units in that system (see, Lakowski, 1971). Although this comparison was not required for the purposes of the present effort, we measured the chromaticity of the primary stimuli in both the Nagel and Kintz anomaloscopes with a Photo Research (Model PR-703A) Fast Spectral Scanner. Chromaticities expressed on the CIE 1976 Uniform-Chromaticity Scale (UCS) are given in Table 2 for the various red/green scale readings of both anomaloscopes. The chromaticities associated with selected scale readings of both anomaloscopes are also shown in Figure 4, along with a portion of the spectrum locus of the CIE 1976 UCS diagram.

Assessing the Validity of the Kintz Anomaloscope

As suggested by the NRC Committee on Vision (1981), the validity of the Kintz anomaloscope as a color vision test was assessed by comparing it to the standard Nagel anomaloscope. The K-statistic (Bishop, Fienberg, & Holland, 1975) was used as a statistical measure of the agreement between the two tests in classifying color-defective subjects. The K-statistic represents the number of agreements between the two tests, divided by the number of possible agreements, with the resulting value adjusted by the number of agreements expected by chance alone. The relevant formula then is:

$$K = \frac{\text{\% of observations for which there is agreement} - \text{\% of agreements expected by chance}}{100\% - \text{\% of agreements expected by chance}}$$

III. RESULTS AND DISCUSSION

Normative Data for the Kintz Anomaloscope

The Rayleigh matching data obtained from the 43 normal trichromats are summarized in Table 3. These subjects were tested using both the method of limits and the method of adjustment. The MMPs and MRs from the method of limits are tabulated in terms of the logarithm to the base 10 of the ratio of the green and red primaries (log G/R, column 1), and also in terms of the proportion of the red primary (R/(R+G), column 2). The MMP, shown in column 3 for the method of adjustment, is the mean of the six settings made by each subject, and the column labeled SD is the standard deviation of those six settings. The log (G/R) transformation has been used previously (e.g., Nelson, 1938) and is provided for comparison of the present data with those of other studies. Our reasons for using the R/(R+G) transformation will be described in due course.

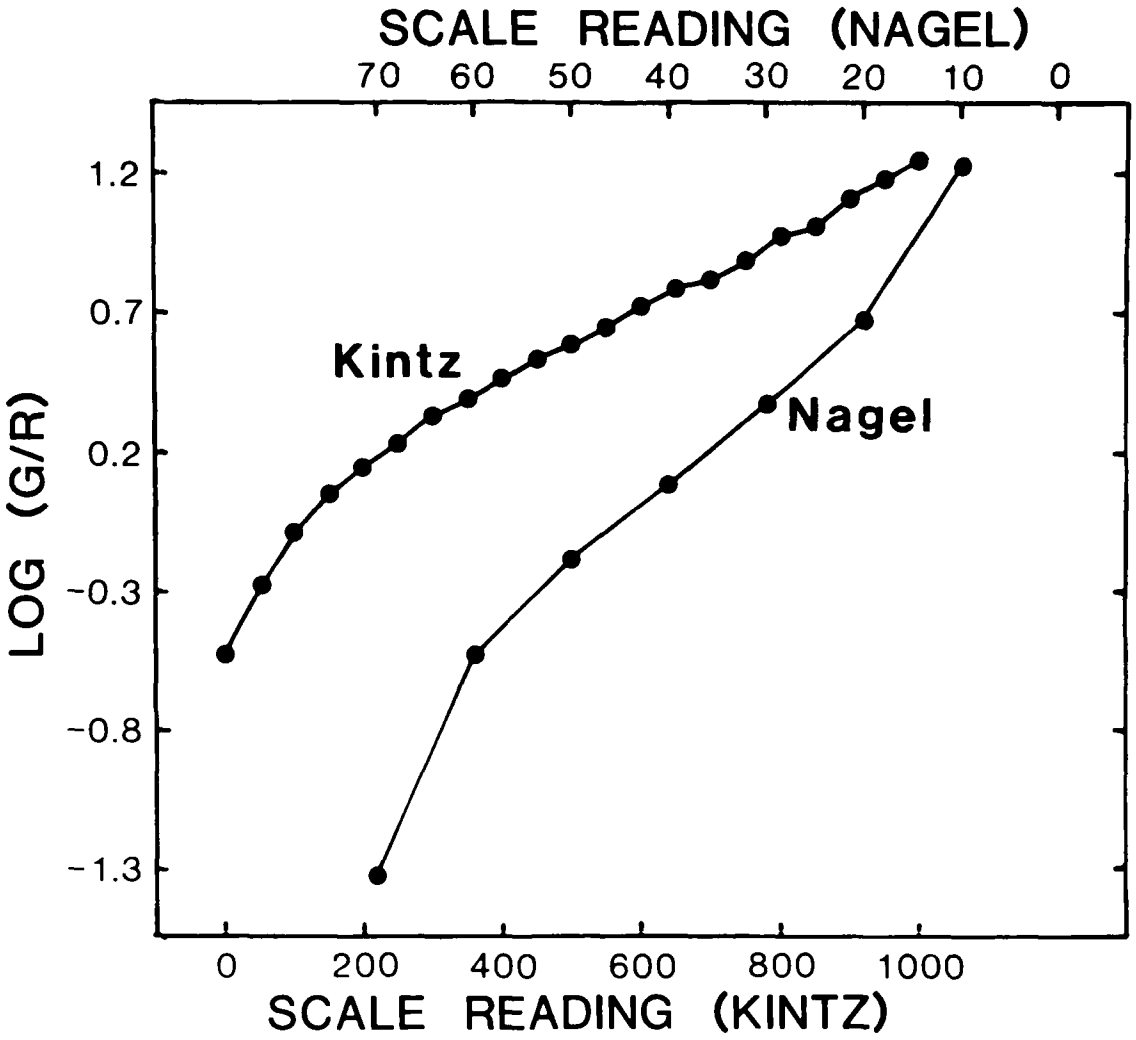

Figure 2. The Output in Units of Log (G/R) of the Primary Field of the Nagel and Kintz Anomaloscopes Used in the Present Study. The luminance of the green primary is denoted by G and that of the red primary by R.

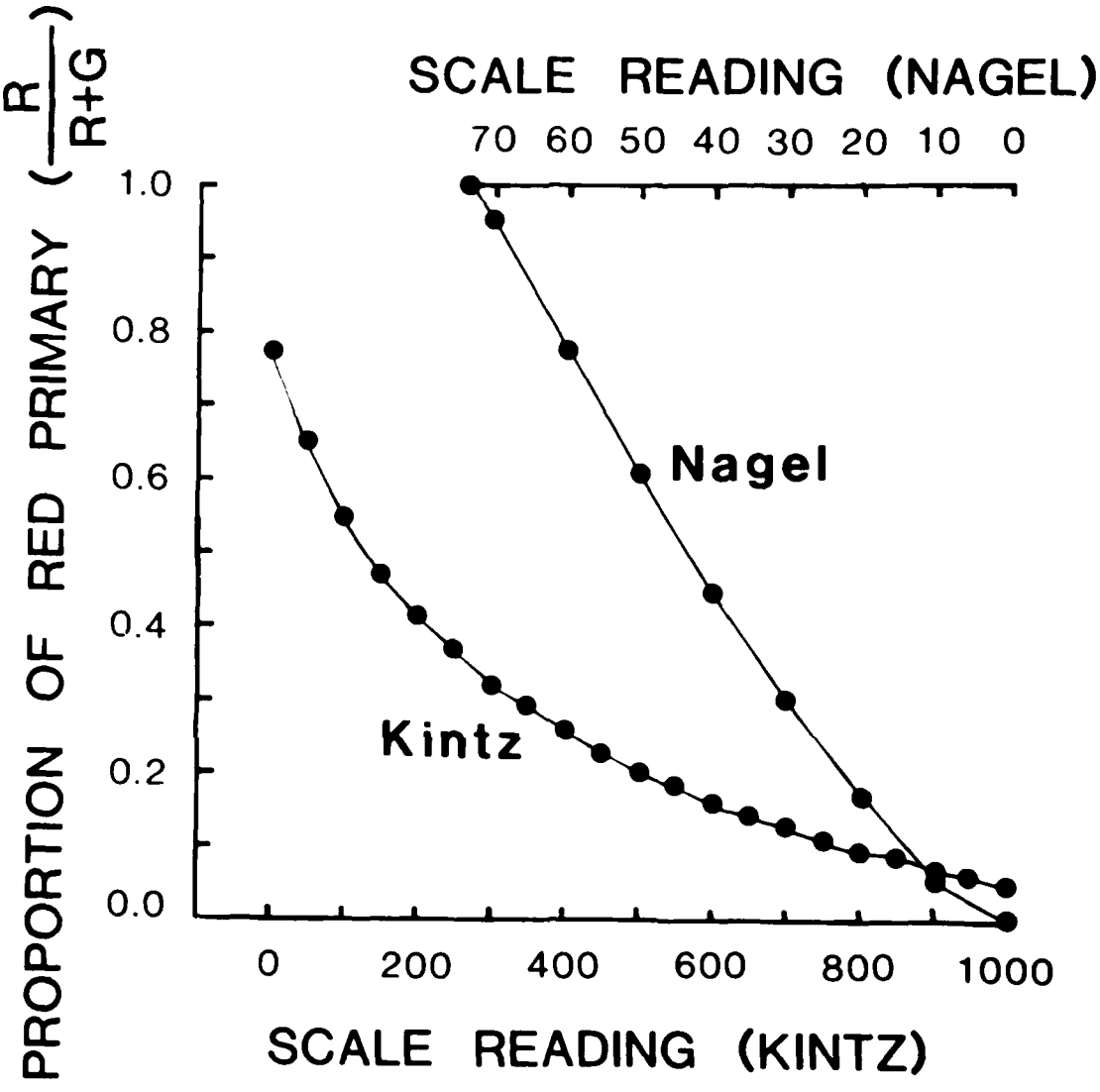

Figure 3. The Output, in Units of R/(R+G), of the Primary Field of the Nagel and Kintz Anomaloscopes Used in the Present Study. The luminance of the green primary is denoted by G and that of the red primary by R.

Table 2. Chromaticities, Expressed in CIE 1976 UCS, for Various Scale Readings on the Kintz and Nagel Anomaloscopes

Kintz			Nagel		
Scale	u'	v'	Scale	u'	v'
0	.4681	.5273	0	.1072	.5822
50	.4319	.5330	5	.1151	.5810
100	.4007	.5375	10	.1426	.5770
150	.3801	.5424	15	.1719	.5727
200	.3567	.5452	20	.2036	.5678
250	.3404	.5474	25	.2381	.5629
300	.3266	.5500	30	.2730	.5574
350	.3143	.5521	35	.3113	.5517
400	.3030	.5538	40	.3483	.5464
450	.2940	.5547	45	.3885	.5404
500	.2855	.5561	50	.4251	.5343
550	.2784	.5575	55	.4639	.5286
600	.2711	.5580	60	.5030	.5225
650	.2648	.5591	65	.5401	.5168
700	.2595	.5596	70	.5778	.5116
750	.2547	.5607	73	.6008	.5084
800	.2506	.5618			
850	.2459	.5622			
900	.2418	.5621			
950	.2382	.5634			
1000	.2346	.5639			

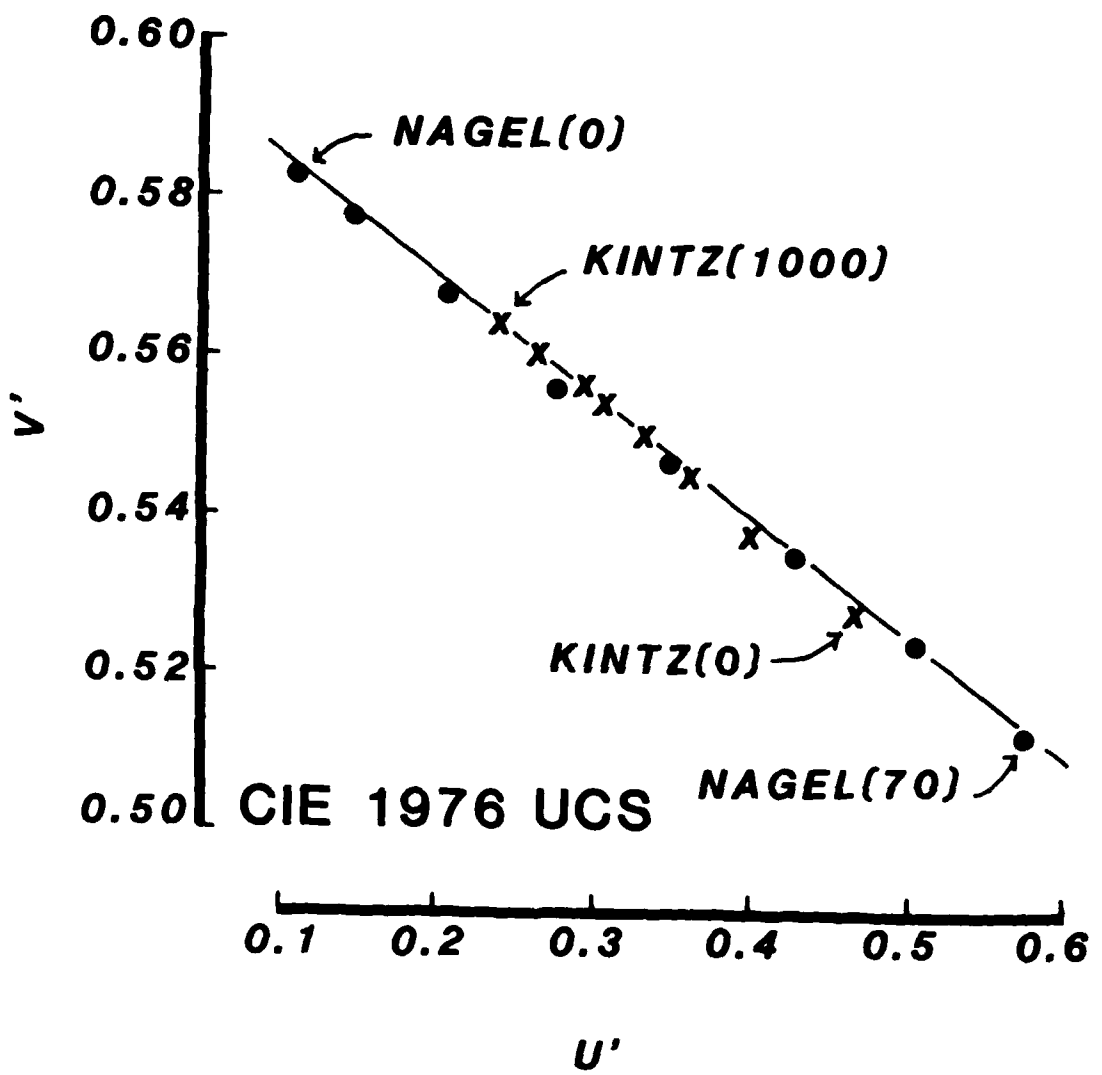

Figure 4. The Chromaticities of Selected Scale Readings on the Nagel and Kintz Anomaloscopes Plotted in CIE 1976 UCS Space. The solid line represents the long-wavelength spectrum locus.

Table 3. Color Matching Data for the 43 Normal Observers Tested on the Kintz Anomaloscope Using Both the Method of Limits and the Method of Adjustment

Subject	(1) log(G/R) (limits) MMP	(1) log(G/R) (limits) MR	(2) R/(R+G) (limits) MMP	(2) R/(R+G) (limits) MR	(3) log (G/R) (adjustment) Mean	(3) log (G/R) (adjustment) SD
1. MC	0.525	0.106	0.223	0.040	0.533	0.072
2. KB	0.515	0.112	0.226	0.051	0.498	0.015
3. TA	0.564	0.066	0.209	0.024	0.559	0.015
4. TR	0.538	0.052	0.218	0.021	0.536	0.026
5. DJ	0.518	0.066	0.227	0.027	0.513	0.027
6. HB	0.578	0.079	0.226	0.051	0.591	0.032
7. BG	0.531	0.066	0.222	0.027	0.528	0.013
8. DH	0.565	0.053	0.208	0.019	0.564	0.022
9. NK	0.604	0.052	0.194	0.018	0.607	0.026
10. BP	0.525	0.053	0.224	0.023	0.532	0.016
11. DL	0.538	0.080	0.219	0.032	0.518	0.037
12. EM	0.492	0.093	0.236	0.045	0.493	0.047
13. MB	0.518	0.118	0.226	0.053	0.514	0.041
14. KD	0.555	0.139	0.213	0.054	0.599	0.044
15. EB	0.551	0.080	0.214	0.030	0.575	0.049
16. GL	0.564	0.066	0.208	0.025	0.588	0.008
17. TH	0.518	0.066	0.227	0.027	0.519	0.008
18. JJ	0.571	0.092	0.208	0.038	0.532	0.033
19. WM	0.597	0.040	0.196	0.014	0.608	0.021
20. JB	0.568	0.047	0.206	0.020	0.577	0.021
21. GG	0.578	0.119	0.238	0.022	0.579	0.040
22. DD	0.488	0.043	0.206	0.046	0.492	0.015
23. GB	0.508	0.039	0.230	0.016	0.515	0.016
24. HW	0.535	0.139	0.223	0.052	0.528	0.046
25. SS	0.571	0.106	0.207	0.040	0.580	0.019
26. TF	0.512	0.079	0.228	0.035	0.537	0.044
27. BW	0.584	0.052	0.201	0.018	0.596	0.011
28. SD	0.594	0.033	0.197	0.012	0.612	0.022
29. JG	0.505	0.053	0.232	0.022	0.500	0.025
30. MT	0.532	0.119	0.223	0.047	0.544	0.056
31. AH	0.548	0.059	0.217	0.032	0.533	0.028
32. KT	0.505	0.079	0.232	0.034	0.537	0.014
33. DC	0.518	0.080	0.227	0.033	0.540	0.033
34. NR	0.545	0.079	0.217	0.032	0.570	0.021
35. PD	0.551	0.118	0.215	0.046	0.561	0.019
36. CB	0.512	0.119	0.230	0.049	0.508	0.049
37. WS	0.525	0.066	0.224	0.026	0.535	0.014
38. TF2	0.499	0.171	0.238	0.073	0.489	0.034
39. NT	0.525	0.066	0.224	0.028	0.546	0.018
40. JL	0.505	0.053	0.232	0.022	0.531	0.081
41. RR	0.538	0.066	0.219	0.027	0.525	0.091
42. SS2	0.571	0.079	0.207	0.029	0.555	0.032
43. WW	0.572	0.093	0.204	0.034	0.594	0.018
Mean =	0.541	0.0800	0.218	0.0329	0.546	0.0298
SD =	0.0301	0.0307	0.0118	0.0133	0.0347	0.0192

The MMP and MR data obtained by the method of limits in units of log (G/R) have been converted to z-scores and plotted in Figures 5a and 5c for the purpose of determining whether their distribution is significantly different from normal. The Lilliefors modification of the standard Kolmogorov-Smirnov test was used (see Conover, 1971). The Lilliefors test is performed on the largest difference between the cumulative normal distribution and the cumulative proportion of the variable of interest. These cumulative functions are shown in Figures 5b and 5d for the MMP and MR data, respectively. The arrow in each graph indicates the largest difference between the two functions. In neither case did the difference exceed the 9.95 quantile; thus, we conclude that the true distributions of the MMP and MR do not differ significantly from normality. It would therefore be appropriate to use sample statistics based on these data in order to classify our color-defective subjects. Pickford (1951), however, found the distribution of MRs to be significantly skewed in a group of 128 color-normal observers and suggested that the modal MR be used in place of population statistics for the purpose of classifying color-defective observers. In the present investigation, we have drawn from both approaches and have established our classification criterion as twice the mean MR (see below).

As noted by Lakowski (1969), the classical technique for obtaining Rayleigh color matches was the method of adjustment whereby the subject was allowed to adjust both the ratio of the red and green primaries and the luminance of the yellow comparison field. Several presumably independent settings were obtained, and their mean was taken as the MMP while their standard deviation gave an indication of the subject's MR. It has become increasingly evident, however, that MMPs and MRs are not well correlated and that an accurate measure of each is required for proper classification of color-defective observers. For this reason, Pickford (1951) and others have suggested that the method of adjustment be replaced by a method of limits procedure wherein the experimenter serially adjusts the red-green primary ratio, and the subject adjusts the luminance of the yellow comparison field in an attempt to obtain a color match. As noted above, we have obtained log (G/R) data for 43 subjects, using both the method of adjustment and the method of limits. Shown in Figure 6 is a scatter plot of the MMP data from the method of limits (ordinate) and the mean setting data from the method of adjustment (abscissa). These data are also given in Table 3 along with summary data. The best-fitting regression line was $Y = 0.782(X) + 0.114$, and the correlation coefficient (r) of 0.889 was highly significant ($p < 10^{-6}$).

It might be expected that the MRs obtained by the method of limits and the standard deviations of the settings obtained by the method of adjustment will be highly correlated. A regression analysis was performed on the MR data in column 1 of Table 3 and the standard deviations shown under the heading SD in column 3 of Table 3. The data of subjects TF2, JL, and RR were omitted since they exceeded the group mean by more than three standard deviations. The resulting correlation coefficient of 0.58 was found to be significant ($p < .01$), and the best-fit regression line was of the form $MR = 1.12(SD) + 0.048$. This equation was used to estimate MRs from the standard deviations obtained from 21 of the 43 normal observers tested on the Nagel anomaloscope. The estimated MRs were, in turn, used to classify the 36 color-defective observers based on their performance on that instrument.

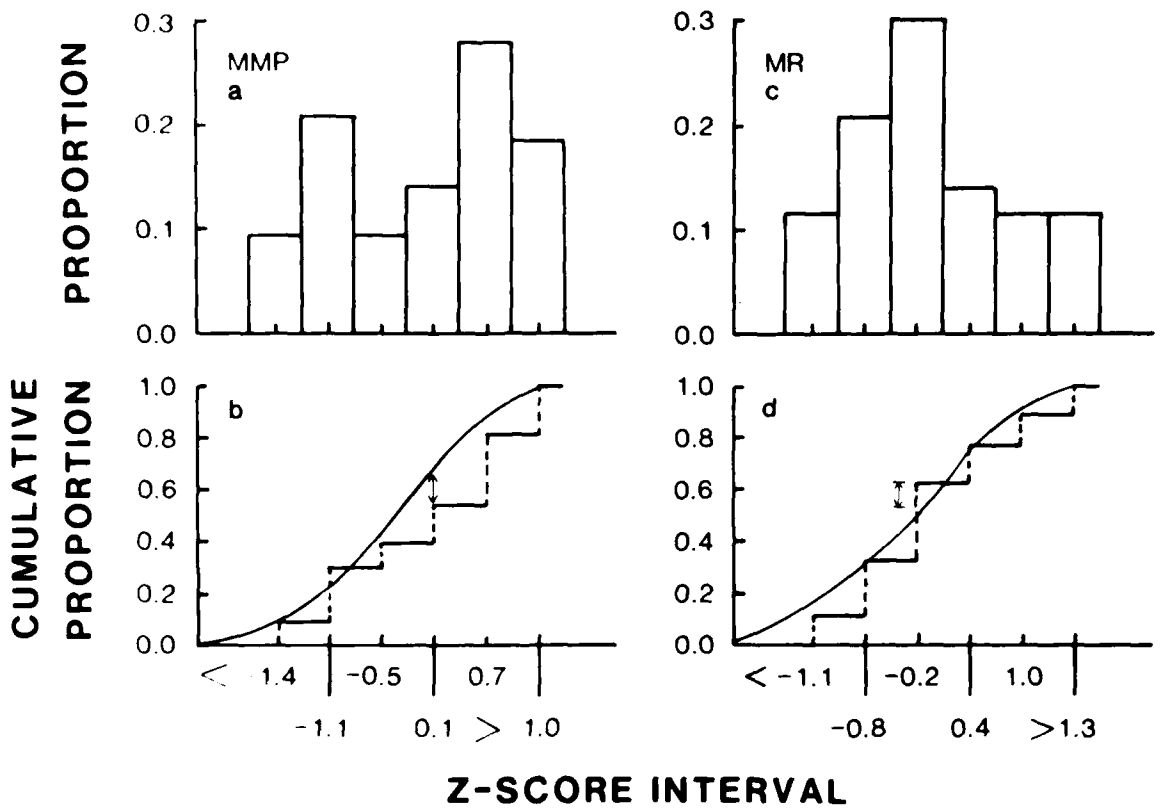

Figure 5. In (a) Is Shown the Normalized Distribution of the Matching Midpoints (MMPs) Obtained From the 43 Normal Observers. Shown in (b) is the cumulative distribution used to test the normalcy of the MMP data as described in the text. In (c) is shown the matching ranges (MRs) obtained from the 43 normal observers. Shown in (d) is the cumulative distribution used to test the normalcy of the MR data as oescribed in the text.

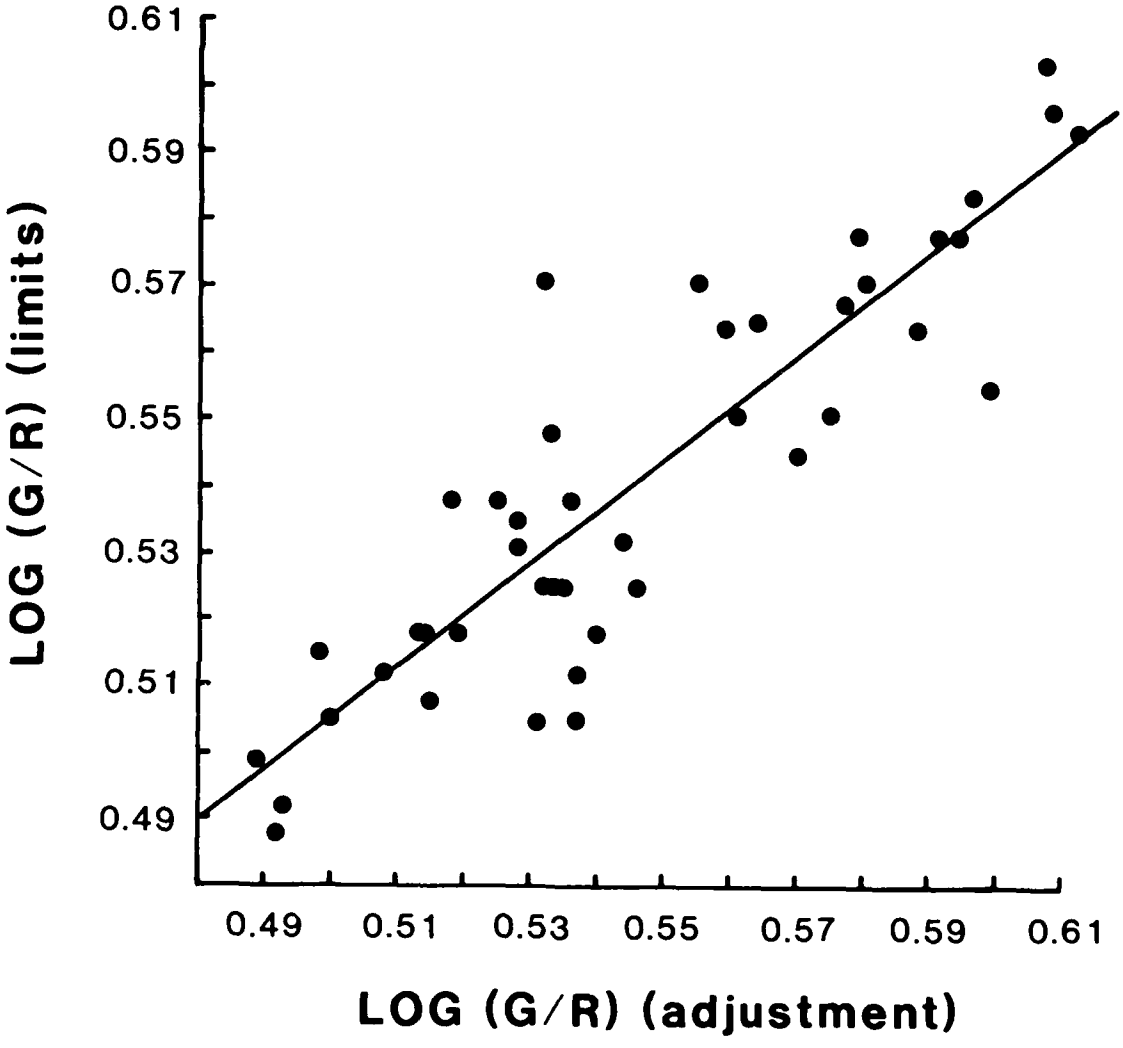

Figure 6. A Scatter Plot of the Matching Midpoint Obtained by the Method of Limits and the Mean of the Match Settings Obtained by the Method of Adjustment Both Expressed in Units of Log (G/R). The best-fit regression line is shown and is defined by "limits" = 0.782 ("adjustment") + 0.114.

Comparison of Classifications Obtained Using the Kintz and Nagel Anomaloscopes

For purposes of comparing the Kintz and Nagel anomaloscopes, we have adopted, with minor modifications, the criteria for classifying red-green color-defective observers proposed by Lakowski (1969) and by the NRC Committee on Vision (1981). By our criteria, there are five categories of red-green color defect defined, based on a standard Rayleigh color match, as follows:

1. color deviant (CD) - a normal MR but an MMP between 1.5 and 3 standard deviations on either side of the normal mean;

2. color weak (CW) - an MR greater than twice the normal mean value, and an MMP within ± 2 standard deviations of the normal mean;

3. simple anomalous trichromat (SA) - an MR less than twice the normal mean value, and an MMP greater than ± 3 standard deviations from the normal mean; observers in this category are classified as either protanomalous (PA) or deuteranomalous (DA);

4. extreme anomalous trichromat (EA) - an MR greater than twice the normal mean value and an MMP greater than ± 3 standard deviations from the normal mean; these observers are classified as either extreme protanomalous (EPA) or extreme deuteranomalous (EDA);

5. dichromat (D) - an MR encompassing both primaries; dichromats are classified as either protanopes (P) or deuteranopes (D).

The MMPs, MRs, and classifications of the five protanomalous and eight deuteranomalous observers of the present investigation, obtained using the Kintz and Nagel anomaloscopes, are shown in Table 4. The two entries for the Kintz anomaloscope represent the test and retest conditions. These entries are given in terms of the proportion of the red primary in the red/green mixture (i.e., R/(R+G)) chosen as a match to the yellow test stimulus. This proportion was used in place of the more common log (G/R), since the latter would be undefined for anomaloscope settings in which either G or R were zero. Our own normative data (see Table 3) were used to classify our protan and deutan observers on both anomaloscopes. A summary of the validity and reliability tests performed on the data of Table 4 are shown in Tables 5a and 5b. All five categories of color-defective vision described earlier were used in the analysis, although only those rows and columns containing at least one non-zero cell are presented in the two tables shown. For the comparison of the Kintz and Nagel anomaloscopes, the K-statistic was found to be 0.73, whereas for the test-retest comparison of the Kintz anomaloscope it was 0.88. Each of the 23 observers classified as dichromatic on the Nagel anomaloscope were also classified as dichromats on both the test and retest trials on the Kintz anomaloscope. In order to assess the validity and reliability of the Kintz anomaloscope for the more difficult discrimination among non-dichromatic color defectives, a further analysis was performed excluding the 23 dichromats. Under these conditions, the extent of agreement in the test-retest comparison was reduced somewhat to 0.57, while it was reduced substantially to 0.07 in the validity comparison. It must be stressed that this latter K-value is low due to the restricted analysis by which it was

Table 4. Matching Ranges, in Units of R/(R+G), and Classification (see text) of the 13 Anomalous Trichromats Each Tested Once on the Nagel Anomaloscope and Twice on the Kintz Anomaloscope

	Kintz 1	Nagel	Kintz 2
protanomalous			
DW	.258-.632 EA	.92-1.00 CD	.112-.632 EA
HF	.053-.652 EA	0-.773 EA	.053-.557 EA
JL	.181-.246 CW	.169-.773 EA	-- --
PB	.053-.694 CW	.371-.940 EA	.053-.632 CW
RC	.203-.441 EA	.780-.863 EA	.368-.540 EA
deuteranomalous			
AM	.053-.229 SA	.113-.246 EA	.053-.194 EA
GH	.053-.284 EA	0-.233 EA	.102-.139 SA
JR	.114-.142 SA	.201-.227 CD	.112-.131 SA
KL	.053-.246 EA	0-.471 EA	-- --
LD	.053-.181 EA	0-.560 EA	.053-.252 EA
LM	.053-.208 EA	0-.195 EA	.062-.284 EA
MA	.089-.139 EA	.056-.275 EA	.071-.172 EA
WD	.053-.213 EA	.141-.304 EA	.053-.224 EA

Table 5. Summary Tables for the Validity and Reliability Tests on the Kintz Anomaloscope

a. VALIDITY

		Nagel		
		CD	EA	D
Kintz (test #1)	CW	0	2	0
	SA	1	1	0
	EA	1	8	0
	D	0	0	23

b. RELIABILITY

		Kintz (test #2)			
		CW	SA	EA	D
Kintz (test #1)	CW	1	0	0	0
	SA	0	1	1	0
	EA	0	1	7	0
	D	0	0	0	23

obtained. That is, it represents the validity of the Kintz anomaloscope in classifying degree of defect over four levels (CD, CW, SA, and EA) in a clinical population tested only once on each instrument. These conditions must be borne in mind when comparing this value with those obtained for other anomaloscopes.

Suggestions for Improving the Kintz Anomaloscope

The relatively complex calibration procedure described earlier for the Kintz anomaloscope was necessary because the timer circuitry as presently designed (see IC1 in Figure 2 of Kintz, 1983) will not allow either the red or green primary to be presented alone. The relative proportion of the red and green primaries, and hence the color of the comparison stimulus, is determined by the duty cycle of the oscillatory square-wave output of IC1. We have determined by visual inspection that a duty cycle of between 0.1% and 0.3% is required for each primary to appear as if it alone is in the "on" state. Kintz (1983) claims that his circuit will allow a duty cycle of about 0.01% which if true would be sufficient to effectively present either primary alone. We have duplicated this circuit and found, however, that the resistance ratio used by Kintz (i.e., $R_2/R_1=10$) allows for a duty cycle of 1% at best and results in a visually significant narrowing of the chromaticity range covered by the LED primaries. Increasing the value of R_2 will extend the duty cycle but, in our experience, also results in substantial variations in the output frequency. We suggest, therefore, that Kintz's IC1 be replaced

by a conventional dual-timer circuit, an example of which is shown in Figure 7. This circuit has the advantage of requiring fewer discrete components, providing for independent control of output frequency and duty cycle, and allowing duty cycles of 0.1% or better.

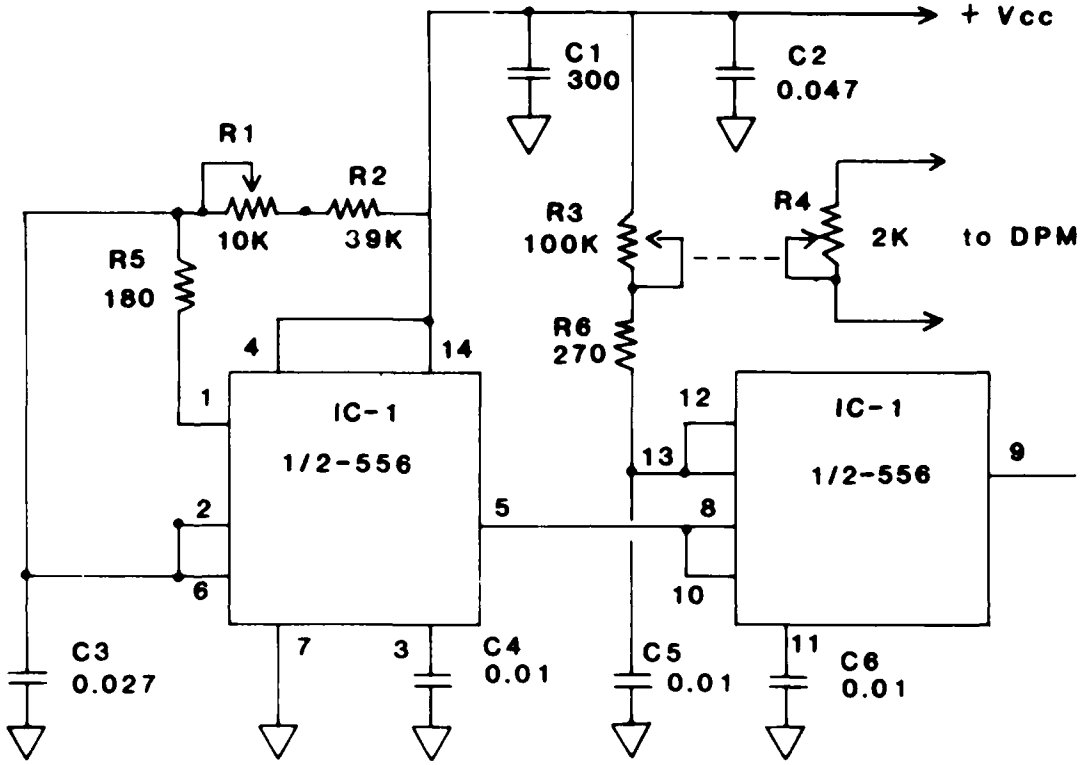

Figure 7. A Schematic Diagram of a Dual-Timer Circuit Providing Independent Control of Frequency and Duty Cycle.

As pointed out by Pokorny and Smith (1984), the precision with which MRs and MMPs can be measured depends largely on the spectral bandwidth and the spectral separation of the anomaloscope primaries. The spectral bandwidths of LED-derived primaries of the Kintz anomaloscope are somewhat greater than those of the Nagel anomaloscope. The data of Figure 2, however, indicate no significant reduction in primary saturation relative to the Nagel anomaloscope, and so spectral bandwidth is probably not a significant limiting factor. A potentially more serious limitation is the spectral separation of the bicolor light bar LEDs. The peak wavelength of the red-LED primary is 635 nm while that of the green is 565 nm, and the result is less separation of these primaries in chromaticity space as compared to those of the Nagel anomaloscope (again, see Figure 2). Since some extreme anomalous trichromats can be distinguished from dichromats only by the extent of their matching range, a reduced separation of the anomaloscope primaries could result in the misclassification, relative to the Nagel, of anomalous trichromats as

dichromats. The data of Table 3 indicate that such a misclassification never occurred in the present study although this may be a fortuitous consequence of the limited matching ranges exhibited by our extreme anomalous trichromats. The problem of primary separation may be ameliorated somewhat in future implementations of the Kintz design by the use of a new bicolor light bar (Hewlett-Packard HLMP-2980) whose green component peaks at about 556 nm (R. Kintz-personal communication). For the present we must conclude that the potential exists for the misclassification of extreme anomalous trichromats as dichromats by the Kintz anomaloscope. Pokorny and Smith (1984) have concluded that LED-based anomaloscopes will require intensive validation. We agree and would further caution against a casual generalization of the present results and conclusions to other solid-state anomaloscopes.

There are also several minor modifications of the Kintz (1983) anomaloscope which we would suggest in the interest of subject and experimenter convenience. Kintz suggests ten-turn potentiometers for controlling the primary ratio (i.e., R/G) and the luminance of the comparison stimulus. Several subjects complained that too many turns were required to obtain a color match, and so we would suggest that three-turn potentiometers be substituted. Also, the turns-counting dials suggested by Kintz are unsuitable for data collection in semi-darkness. We have recently constructed a solid-state anomaloscope using panel meters whose display intensity can be adjusted in accordance with the ambient illumination. One possible implementation of a digital panel meter (DPM) into the solid-state design is also shown in Figure 7. Finally, in the absence of detailed information on the long-term stability of LED bicolor light bars, it would be prudent to periodically check the luminance of the three sets of LEDs used in the solid-state design. Test points for monitoring the various timer inputs to the light bars would greatly facilitate comparison of these inputs with the LED outputs as measured by an external detector.

IV. CONCLUSIONS

The Kintz anomaloscope primaries are less separated in chromaticity space than are those of the Nagel anomaloscope. This is due to the greater spectral bandwidth of the Kintz primaries which increases their luminance but also renders them less spectrally pure. Although this may appear to be a major limitation of the Kintz anomaloscope, we found no evidence that anomalous trichromats were incorrectly classified as dichromats.

When all color defectives were considered, both the validity and reliability of the Kintz anomaloscope were found to be high. When only anomalous trichromats were considered, however, the validity was substantially reduced. This reduction can be attributed to variations in classification based on the degree of color defect, since the Kintz anomaloscope accurately distinguishes dichromats from all other color defectives.

Consequently, the solid-state anomaloscope is an acceptable alternative to conventional anomaloscopes, and its relatively low cost, optical simplicity, and portability make it potentially useful for the screening of large numbers of individuals as required, for instance, by the armed forces.

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